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Cooperation of human and machines in assembly lines

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ABSTRACT

Flexibility and changeability of assembly processes require a close cooperation between the worker and the automated assembly system. The interaction between human and robots improves the efficiency of individual complex assembly processes, particularly when a robot serves as an intelligent assistant. The paper gives a survey about forms of human–machine cooperation in assembly and available technologies that support the cooperation. Organizational and economic aspects of cooperative assembly including efficient component supply and logistics are also discussed.

1. Introduction

Skilled robotic systems are key components in fully automated assembly processes as a part of a highly efficient production. Due to smaller lot sizes of customized products the demands for increased flexibility and adaptability to changing assembly tasks are rising continuously. Therefore a robot assisted but human guided assembly has various significant advantages compared to full automation [1].

Flexibility and changeability of assembly processes require a close linkage between the worker and the automated assembly system. The interaction between human and robot improves complex assembly processes, particularly when a robot can be guided by a worker and the robot provides power assistance to the worker.

Various forms of support can be provided to the worker in manufacturing processes, depending on the degree of assistance with sensors, actuators or data processing (Fig. 1). For assembly processes robot assistance combines these components in order to give support for difficult, monotonous or exhausting tasks.

2. Human–machine cooperation in assembly lines – state of the art

2.1. Hybrid assembly

The close linkage of human and machine in cooperative assembly tasks should make use of the strengths of both sides. Typically an automated assembly system provides a couple of advantages such as operation without breaks and fatigue and high productivity for simple assembly tasks. Though, flexibility of automated systems such as robots normally is restricted due to high programming effort and limited abilities for handling of complex or limp parts.

On the other hand a human provides incomparable senso-motoric abilities for complex handling tasks, can quickly adapt to new process sequences but is restricted in force and precision. Cooperative work stations combine the advantages of a human and an automated system (Fig. 2).

One way of utilizing robotic and human capabilities at their best is obtained in assembly system where there is a sequential division of tasks. The simple tasks suited for robots are found upstream in the line. The complex frequently varied tasks that give the assembled products their individual features are performed downstream by human operators. Such hybrid lines have been used to advantage in industry for more than two decades [1,4].

Today, especially for the assembly of heavy or bulky parts, weight compensators/balancers are used. Since these systems do not compensate for inertial forces, even small mistakes lead to work-related injuries (lower back pain, spine injuries) [5]. According to statistics of the Occupational Safety & Health Department (OSHA) of the US Department of Labour [6], more than 30% of European manufacturing workers are affected by lower back pain which brings with it enormous social and economic costs. In order to improve this situation, a careful design of so-called intelligent assist systems (IAS) or intelligent automation devices (IAD) and their operating procedures is necessary when physical collaboration between machines and human workers also have to follow ergonomic targets. Fig. 3 shows an IAD for cockpit assembly.Industrial applications of human–machine cooperation are mainly to be found in automotive industry. Stanley Automation [7] provides IADs, which support the worker in assembly tasks such as

- axle sequencing,
- cardboard blank handling,
- catalytic converter test cell,

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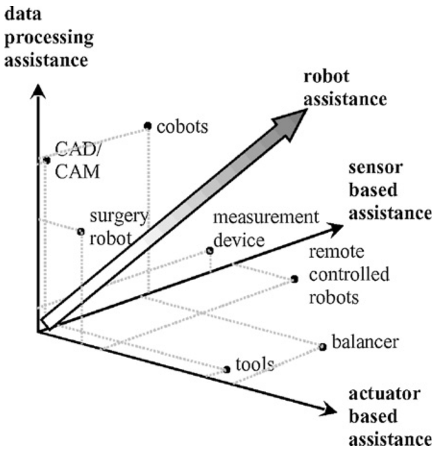

Fig. 1. Influence factors on robot assistance [2].

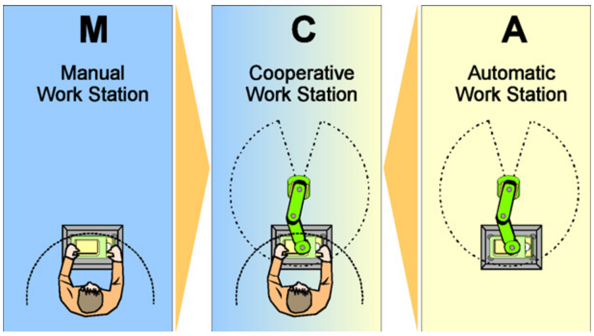

Fig. 2. Combination of a manual and an automatic work station [3].

- engine block handling,
- floor pan transfer,
- front sub-frame transfer,
- instrument panel load,
- strut handling,
- transmission handling and
- transmission sequencing.

This IAD technology was originally developed by the US company Cobotics in 2003 and is based on fundamental research done by Colgate and Peshkin [8]. Further research for so-called power amplifying assist devices (IPAD) was done by Fraunhofer IPK [3] (Fig. 4).

Hybrid assembly systems can be divided into two groups:

- workplace sharing systems and
- workplace and time sharing systems.

Fig. 3. Cockpit install with IAD [7].

2.2. Workplace sharing systems

In workplace sharing systems robots and human beings are both working in the same workplace, and both are performing handling tasks as well as assembly tasks in two different configurations:

- Either the robot is performing an assembly task and the human worker is performing a handling task,
- or the robot is performing a handling task and the human worker is performing an assembly task.

The interaction of the robot and the human worker is limited to the avoidance of collisions; the robot will stop if the distance between robot and human being is below a given security distance.

Fig. 5 shows an example of a workplace sharing hybrid system: the team@work system of Fraunhofer IPA and IPK [9]. In this scenario several components have to be assembled on a sheet metal part which is supplied by a conveyor system. The human worker has to grip the components out of bins, in order to transport these parts towards the conveyor system (handling time) and to put the components on the sheet metal parts (assembly). Afterwards, the robot has to screw these components into the

Fig. 4. IPAD – a reliable approach for advanced material handling [3].

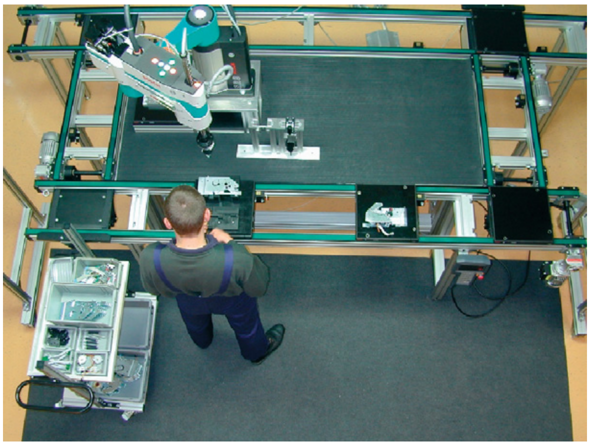

Fig. 5. Example of a workplace sharing hybrid system (team@work [9]).

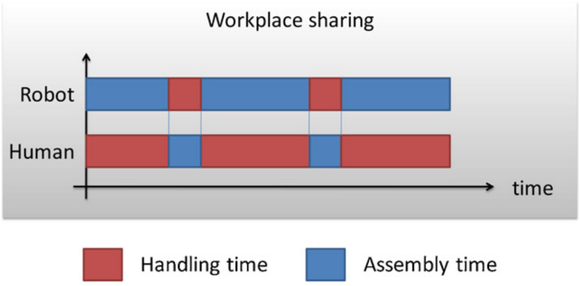

Fig. 6. Time distribution between human and robot in workplace sharing systems.

sheet metal part (assembly). If the worker is too slow, the robot will wait until the worker has finished his tasks [9].

The task distribution between robot and human worker in this scenario is as follows (Fig. 6).

2.3. Workplace and time sharing systems

In workplace and time sharing systems the human worker and robot are additionally able to jointly perform a handling task or an assembly task at the same time, i.e. there are four different configurations:

- the robot is performing an assembly task and the human worker is performing a handling task,
- the robot is performing a handling task and the human worker is performing an assembly task,
- the robot and the human worker are jointly performing a handling task and
- the robot and the human worker are jointly performing an assembly task.

In order to jointly handle or assemble objects the robot has to interact with the human worker on a level which is much higher than just the avoidance of collision.

In the scenario which is shown in Fig. 7, the PowerMate system of Fraunhofer IPA [10], the interaction between robot and human worker is realized with a force-torque-sensor which enables that the robot can be moved by the human operator.

The task of this hybrid system is to assemble heavy parts of an automotive rear axle. In order to do this, the robot has to grip part A out of a box and has to move it to the human worker. As these movements take place in an area where the human operator has no access the robot is allowed to move at maximum speed. As soon as this part is in the shared workspace the robot stops and changes to a cooperation mode. In this cooperation mode the human worker is able to move the robot by pushing, pulling or turning a special handling device which is mounted at the robot gripper in combination with a force-torque-sensor.

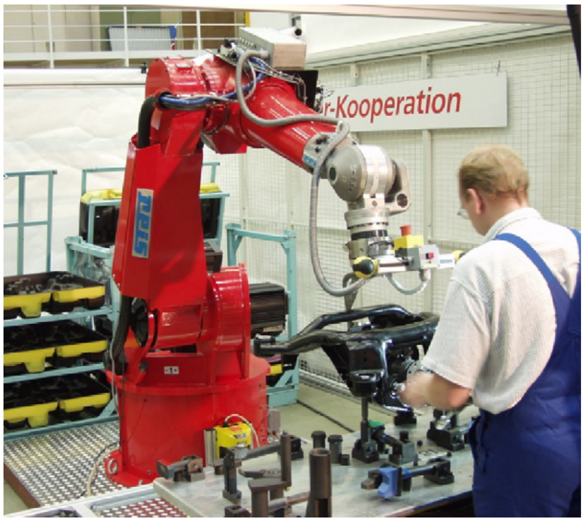

Fig. 7. Example of a workplace and time sharing hybrid system (PowerMate [10]).

In this cooperation mode the human operator is able to ensure a very precise positioning of part A, so that part A can easily be assembled with part B. As soon as this task is done, the robot moves part AB to a second bin and moves back to the first bin in order to pick part A′. In between the human operator prepares part B′ which will be assembly with part A′ in the next cycle.

The task distribution between robot and human worker in this scenario is as follows (Fig. 8).

In this scenario the robot serves like an intelligent and powerful tool to the human operator. The research project PISA deals with flexible assembly systems through workplace sharing and time sharing human–machine cooperation [11]. The focus of the project is on novel intelligent assist systems, planning tools for their integration as well as reconfigurability and reusability of assembly equipment. The overall goal is to keep human workers in the loop but to support them with powerful tools. With respect to the design of a sustainable production several criteria can be improved using human–robot interaction in assembly.

3. Technologies for cooperative assembly

3.1. Interfaces between human and machines

For the efficient cooperation and interaction the human–machine-interface has an essential role. Interfaces for hybrid assembly systems can be divided into two classes:

- remote interfaces such as visual interfaces, interfaces for gestures [12] and voice and
- physical interfaces such as haptic interfaces, displays and head mounted displays (HMDs) as well as force feedback systems.

Robotic systems are typically operated via teach panels or graphical user interfaces. An intuitive way of commanding a

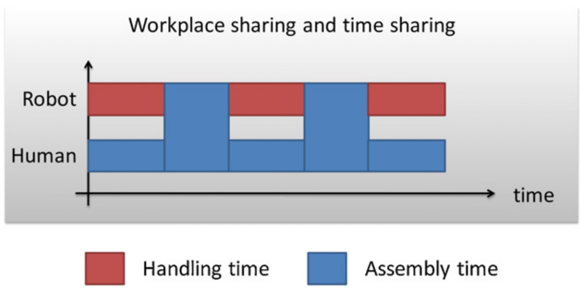

Fig. 8. Time distribution between human and robot in workplace and time sharing systems.

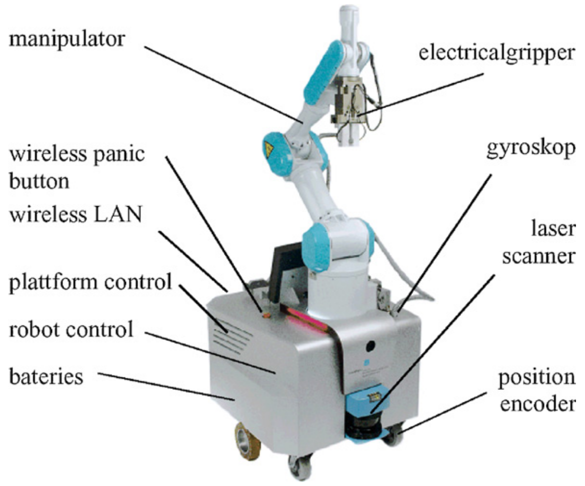

Fig. 9. Hardware architecture of rob@work [17].

mobile robot assistant can be achieved by verbal or gesture commands [13–15]. Due to environmental noise in assembly lines voice control of a robot may be problematic whereas guidance by gestures may provide a robust form of communication between human and robot for short range remote control. The disadvantage of the use of voice or gesture is the single direction control providing only visual feedback of robot motion. For many types of assembly tasks a closer interaction between human and robot is needed, which includes a direct physical contact between both. So-called admittance displays provide force feedback enabling the operator to feel the contact between robot and assembly target by rendering the contact impedance of the robot environment to the human [3,8].

3.2. Robotics

3.2.1. Assist robots

Helms et al. [16] define a robot assistant as a *direct interacting*, *flexible* device, that provides *sensor* based, *actuator* based and *data processing* assistance.

The assist robot rob@work was designed by the Fraunhofer Institute IPA. It is a complex mechatronic system consisting of a mobile platform with differential gear drive, energy supply for 9 h of work and a control system. Different tools such as welding devices or drilling machines can be plugged to the seven DOF manipulator. Target applications for rob@work are to be seen in small series and lot size one manufacturing as well as in maintenance tasks (Fig. 9).

The *SMErobot*™ initiative [18] offers an escape out of the automation trap through:

- Technology development robot systems for small and medium enterprises (SME) adaptable to varying degrees of automation, at a third of today's automation life-cycle costs,
- new business models creating options for financing and operating robot automation given uncertainties in product volumes and life-times and to varying workforce qualification,
- empowering the supply chain of robot automation by focusing on the needs and culture of SME manufacturing with regard to planning, operation and maintenance.

An example of a robot assist system realized in the *SMErobot*™ initiative shows Fig. 10.

Issofidis et al. introduced an anthropomorphic robot assistant for human environment based on a seven degree of freedom (DOF) manipulator arm in combination with a two DOF stereo camera head [19]. The robotic system comprises an interface to the worker for the interactive correction of grasping orientation of the end effector.

Fig. 10. Robotic assist system [18].

3.2.2. Collaborative robots (COBOTS)

Collaborative robots or cobots invented by Edward Colgate [8,20] are mechanical devices that provide guidance through the use of servomotors, while a human operator provides motive power. Cobots can provide a virtual surface used to constrain and guide the workers motion.

Another important difference of Cobots compared with simple balancers is the ability to provide power support to the worker in a way that apparent inertia of heavy work pieces can be reduced by a factor ten or more, which means that physical strain of the worker during handling of large work pieces is reduced significantly (Figs. 11 and 12).

For the support of the worker during handling tasks with heavy loads exoskeleton systems represent an alternative approach. Due to the tight coupling between the robotic axis the force control of the robotic system is complex [21]. Compared with collaborative robots

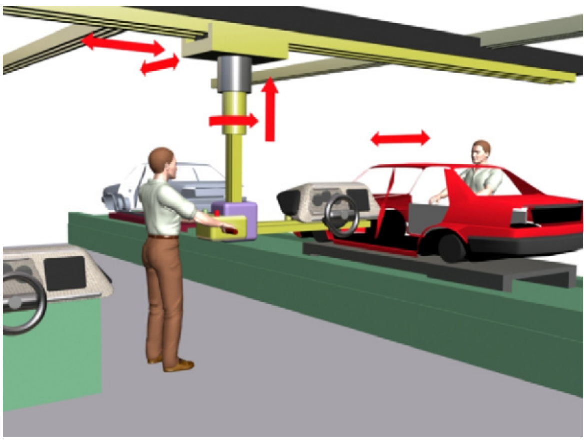

Fig. 11. Rail crane based cobot concept for assembly [3].

Fig. 12. Rail crane based cobotic system providing power supply in order to reduce apparent inertia of heavy workpieces [23,24].

the exoskeleton systems provide a higher degree of mobility but on the other hand adaptation to the human body is time-consuming.

Direct interaction between human and robot is also applied in surgery. In these applications dynamic constraints are applied in order to control the authorized motions of the surgical tool held by the human operator during a planned task [22].

3.2.3. Robustness and stability of human–robot interaction

The most popular method of controlling physical human–robot interaction is to vary the robots end point impedance by appropriate control strategies. Thereby an implementation of haptic displays is possible by displaying varying impedances/admittances at the interaction point of human and robot.

Guaranteeing robust stability turned out to be a crucial challenge of such interactive systems. Therefore the coupled stability of interactive robots has been a subject of intensive research in the past 25 years.

A variety of frameworks for coupled stability of interactive robots have been developed but especially when interacting with unpredictable environments like a human problems remain with these frameworks.

Hogan and Colgate proposed a controller design framework using passivity of the controlled robot as a design criterion [25,26]. For long years this was the major method for designing interactive controllers and a variety of advanced methods were developed on this foundation. One of those advanced method is natural admittance control (NAC) [27].

Hannaford derived a two-port framework to describe the interaction of users with virtual environments via haptic interfaces. Using this framework he describes stable haptic interaction using passivity criteria [1,28,29].

For handling heavy objects comparatively stiff and heavy robots are needed. The performance of a haptic interface to such a robot based on above mentioned methods is very limited. Several research groups [30,31] have derived methods of improving performance in high force haptics using environment models and a robust control framework [1,29,31–34].

3.2.4. Interactive learning of assist robot

Fig. 13 shows a robot system, for which interactive control by the worker is realized through pointing to objects with laser pointers. Within the SME Robot Project [18] technology for simplified teaching the robot by guidance was developed based on force-torque-sensors (Fig. 14).

3.2.5. Humanoid/anthropomorphic robotic systems

A future flexible assembly line will incorporate different workplace types varying from fully automated work cells to manual assembly places. Between these extremes different types of cooperation and interaction between human and robot are applied to achieve maximum flexibility. For this purpose a

Fig. 13. The worker is pointing out objects directly in the scene using a laser pointer [35].

Fig. 14. Teaching the robot by manual guidance using force-torque-sensors [18].

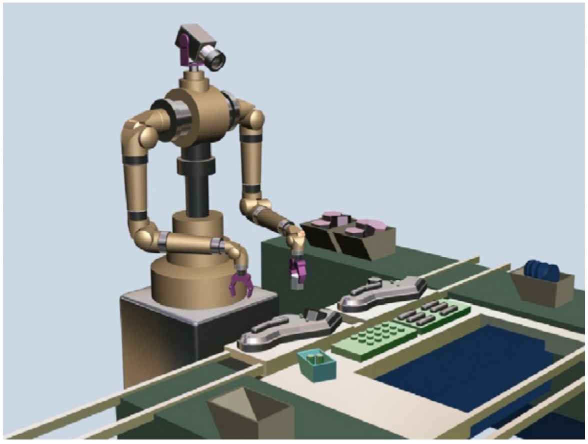

Fig. 15. Humanoid portable robot for flexible assembly [36,37].

humanoid two-arm manipulation robot which can perform complex tasks can work at a human's workplace (Fig. 15).

Besides the humanoid construction the major difference of the robot arm shown in Fig. 16 compared to industrial robots is its light weight structure providing intrinsic safety.

The Deutsches Zentrum für Luft- und Raumfahrt (DLR) designed humanoid robots for application areas which are generally not covered by industrial robots, but are still ongoing research topics.

Typical examples are:

- Assembly processes for which the position estimation for the mating parts and/or the positioning accuracy of the robot is significantly below the assembly tolerance,

Fig. 16. Humanoid light weight robot structure [38].

- applications in which the robot works in immediate vicinity of humans and possibly in direct physical cooperation with them,
- mobile service robotics applications (arms mounted on mobile platforms), for which the information about the position of the robot and the surrounding objects, as well as about the dimension of these objects is afflicted with relatively high uncertainty [38].

3.2.6. Portable robots

The workspace of portable assist systems is not restricted to the place of its actual use but can be chosen within the production environment. This innovation comprises a couple of advantages for manufacturing and assembly:

- Due to a parallel task operation of man and machine, efficiency can be increased,
- cost reduction and improvement of ergonomics is achieved by use of the specific strengths of human and machine,
- flexibility and adaptability with respect to place of installation of handling technology, capacity, experience and knowledge of staff and also with respect to type and complexity of the assembly task can be improved [2].

In order to improve the flexibility of industrial robots for material handling, a portable robot system has been developed by Brecher et al. [39] within the project PORTHOS.

The robot system can be installed at machine tools for feeding of workpieces (Fig. 17). For the generation of robot programs a programming system is introduced that combines the traditional approaches of online- and offline-programming in order to allow fast and easy reprogramming of material handling tasks. The main feature of the programming system is an intuitive user-interface that can be operated without special qualifications.

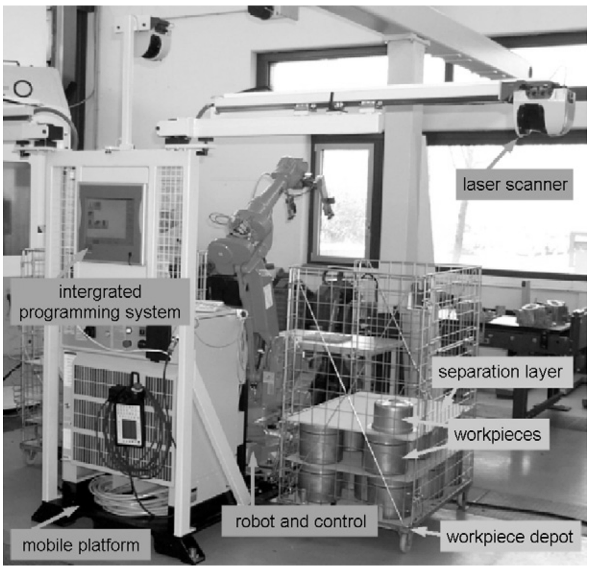

Fig. 17. Setup of the PORTHOS robot system [39].

3.3. Sensors and actuators

Besides advanced control strategies to achieve a compliant and thereby safe robot behaviour a second approach favours the use of inherently compliant actuators to guarantee safety during human–robot interaction [40,41].

The main design goals of the DLR lightweight robots (Fig. 18) were to build a manipulator with kinematic redundancy similar to the human arm, i.e. with seven degrees of freedom (DOF), a load-to-weight ratio of approximately 1:1 where industrial robots typically have a ratio of 1:10 or lower, a total system weight of less than 15 kg for arms with a work space of up to 1.5 m, and a high dynamic performance. There should be no bulky wiring on the robot and no electronics cabinet as usually required by typical industrial robots.

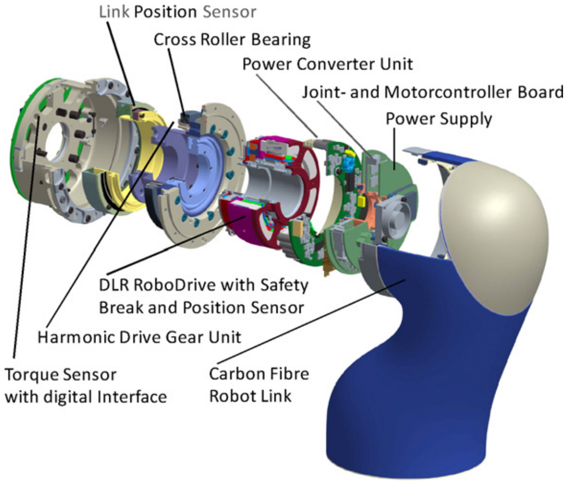

Fig. 18. The mechatronic joint design of the LWR including actuation, electronics, and sensing [38].

The full state measurement in all joints is performed in a 3 kHz cycle, using

- strain gauge-based torque-sensing,
- motor position sensing based on magneto-resistive encoders, and
- link-side position sensing based on potentiometers (used only as redundant sensors for safety considerations).

3.4. Safety systems

The desired coexistence of robotic systems and humans in the same physical domain, by sharing the same workspace and cooperating in a physical manner, poses the very fundamental problem of ensuring safety for the user and the robot.

The European norm "DIN EN 775 Safety of manipulating robots" which is right now revised and converted into the international standard "ISO 10218: Robots for industrial environments – Safety requirements" forms the current basis for safety in a robot cell. Already with the implementation of the DIN EN 775 the possible installation of a robot system within reach of a human was considered under highest security conditions. One of the targets of the ISO 10218 now is to further provide regulations for the robot–human-cooperation [42]. Fig. 19 shows the safety-related steps from classical robot cells to human–robot interaction.

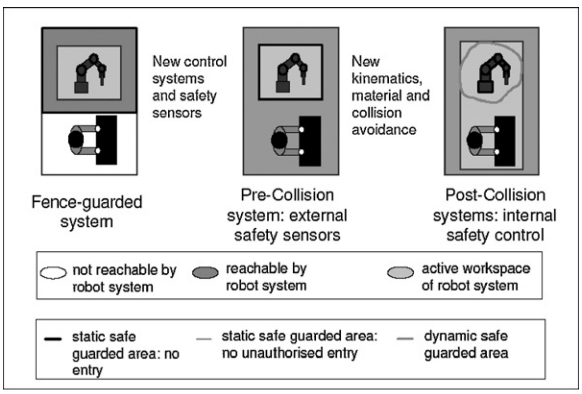

Fig. 19. Safety control – from the classical robot cell to human–robot interaction [42].

Fig. 20. Safety controller for robot assisted welding [43].

3.4.1. Pre-collision systems – control based limitations and sensor based surveillance of the workspace

REIS-Robotics introduced a control feature for their robot systems, with which flexibly programmable limitations for automatic operation can be defined. The robot arm exclusively moves within these restricted areas (Fig. 20). These regions can be programmed by direct teach-in, which means in a haptic way by use of a 6-DOF-sensor at the end effector, or in a classical way by teach-in panel or offline-programming/robot simulation system.

The changing characteristics of robot processes, with increasing payloads, work ranges and cycle times necessitate a more flexible approach to safety, which cannot be addressed with traditional methods. Conventional safety relay technology has also restricted functionality of safety systems, particularly in terms of flexibility and diagnostics. Kuka Roboter GmbH has developed a safety system for industrial robots incorporating the safety-related fieldbus, SafetyBUS p, in cooperation with Pilz GmbH. The Electronic Safety Circuit (ESC), coupled with SafetyBUS p and Pilz PSS safety controllers, is now being used by BMW at its Body-in-White line in Dingolfing, Germany [44].

Standard automated optical protection devices use laser scanner technology in order to separate the human from the robot. The major supplier for these type of safety systems for automated assembly is the German company SICK [45]. Fig. 21 demonstrates the use of SICK active opto-electronic protection devices (AOPD) in assembly.

SafetyEYE by Pilz is a camera System for 3D workplace surveillance (Fig. 22). It is meant to erase the need for safety fences separating the robot workspace from the worker [46]. The system has a sensing device, a computer, and a programmable safety and control system. The sensing device has three cameras (Fig. 22 upper part). The computer receives the camera's image data via fiber-optic cables and creates a three-dimensional image using complex algorithms. This image is then superimposed over the detection zones image to see any zone violation. The computer gives results to the safety system controller, which is the interface

Fig. 21. Application of active opto-electronic protection devices in assembly [45].

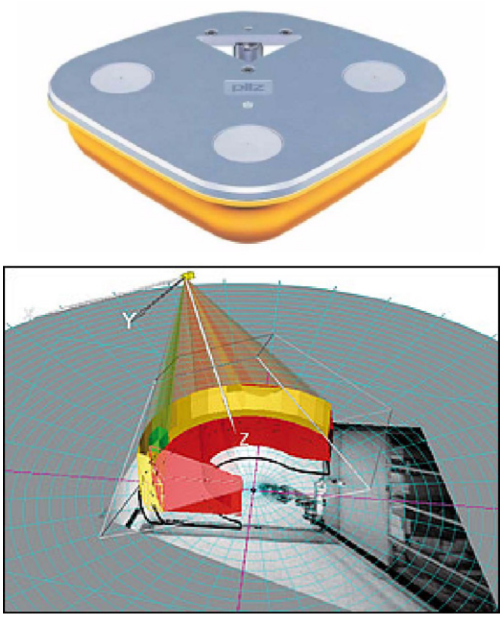

Fig. 22. SafetyEYE camera for workplace surveillance [46].

to the machine controller. If a detection zone has been violated, the configurable outputs are shut down. Typically, the sensing device is located above the workstation for an overview of the robot's operating range (Fig. 22 lower part). When a worker enters the immediate danger zone, there will be an emergency stop to the work. When a worker enters the zone where the robot would take several seconds to reach, the controls reduce the robot speed. When the worker steps back, the robot returns to normal speed.

For safe human–robot interaction besides sensor and interaction concepts the robot control architecture is an important component to ensure safe operation of the robot. Therefore failsafe robot controllers are developed which enable the worker to be resident in robots workspace during operation. The first safe robot control was developed by Kuka followed by solutions by Reis, ABB and Fanuc [47]. Kuka's solution is strictly software based and relies on the severely improved system response time to failures by handing over safety responsibilities directly to the robot controller. The solution by Reis in contrast relies on an additional safety controller monitoring robot operation. This results in a redundant control architecture. The different concepts enable a worker to enter the robot's workspace while the task is still in progress by slowing robot operation to a safe motion speed.

For close forms of cooperation, it is essential not only to detect motion in 3D but also to have an exact surveillance of the worker body. A stereoscopic approach for 3D tracking of the worker body was developed by Fraunhofer IPK in a cooperation with Fraunhofer IPA within the project team@work [48]. The system is able to detect segments of skin within the images (Fig. 23b) in order to find characteristic points of the body. Based on this skin detection the photogrammetric 3D capturing of the body is processed.

Another system that enables close forms of cooperation is a PMD camera based flexible workspace surveillance system developed by Fraunhofer IPA. The concept of this system is to use the cameras distance data and the robot joint angles as input, and to generate a signal as output which can switch between no risk, warn and stop [49].

The acquired distance data from the PMD camera is being preprocessed, the foreground extracted, rectified and meshed in Cartesian space to get the surface of the objects residing inside the workspace. Additionally, the robot is being modelled online in Cartesian space. By comparing both object representations, robot model and objects seen from the camera, the robot can be identified inside the camera object data. All no-robot-data is treated as obstacle and evaluated against safety areas surrounding the robot [49].

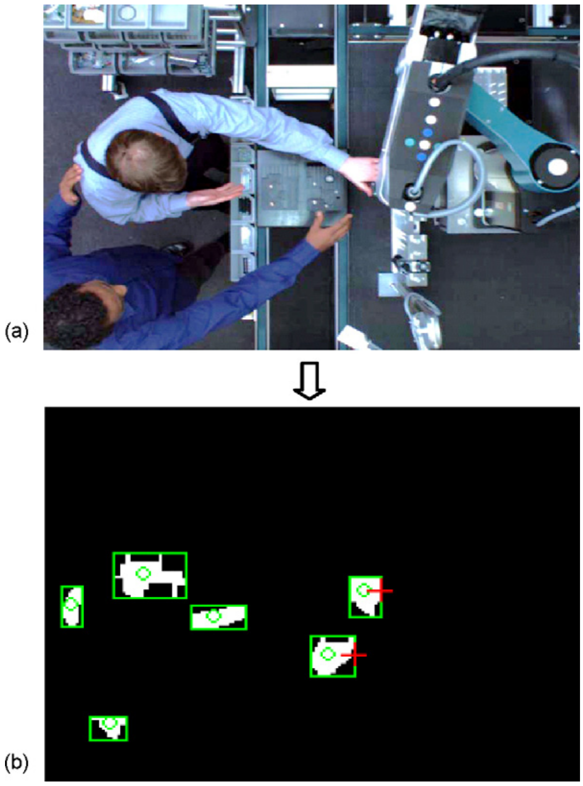

Fig. 23. Stereo camera based surveillance of human–robot-cooperation, live image (a) and detected relevant areas (b) [48].

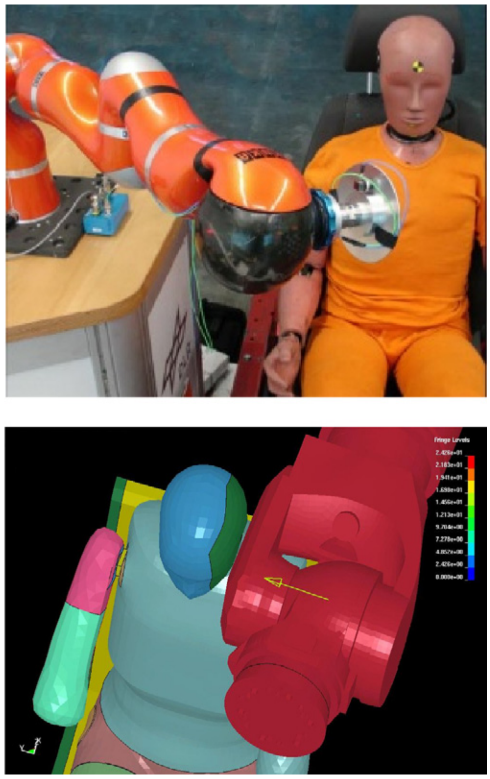

Fig. 25. Impact tests performed by DLR and Fraunhofer IPA [42,52–54].

Fig. 24 shows how a person whose arm is intruding into the dynamic safety area of the robot can be detected with this system.

Krüger et al. [50] developed PMD camera based methods for human motion analysis, which can be applied for workspace surveillance as well as for synchronisation of human and robot motion in cooperative assembly tasks.

3.4.2. Post-collision systems – robot integrated sensors and light weight structures

Joint torque sensing, together with a good robot model are used within the LWR software for fast detection of collision or failure by an integrated torque observer. Inputs to the observer are the joint torques and motor positions. In order to indicate the resulting level of injury, so-called severity indices were evaluated. In the following section the results of the Head Injury Criterion (HIC) are shown, but other indices for the head, neck, and chest were measured as well. The HIC evaluates the resulting head acceleration during an impact. It is the most prominent and widely used measure to quantify the injury level of human beings caused by car accidents and was introduced to robotics in [51,52].Oberer and Schraft extended these tests to impacts of head, chest and lower extremities applying industrial robots (Fig. 25). The resulting Head Injury Index (HIC), the Viscous Criteria (VC) for the chest and the Pubic Symphysis Peak Force (PSPF) for the pelvis are discussed, showing their potential and limitations for the situation in robotics.

Fig. 26 shows the results of HIC-measurements for different types of robots and impact velocities up to 2 m/s. By means of typical severity indices from automobile crash testing even an impact of a huge robot such as the KR500 cannot pose a significant threat to the human head.

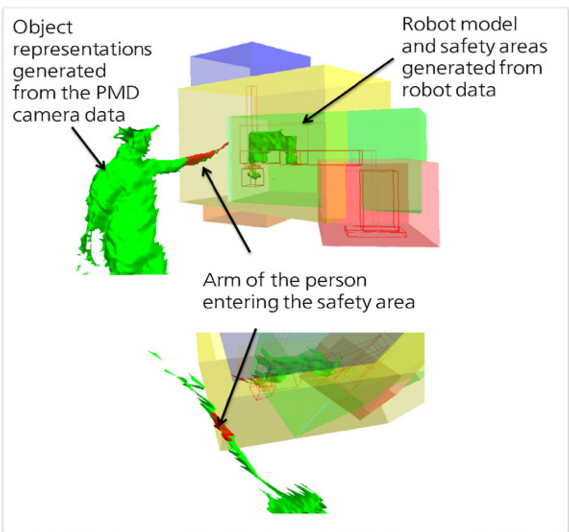

Fig. 24. Detection of a persons intruding arm: triangles marked in red are located inside the yellow safety area [49].

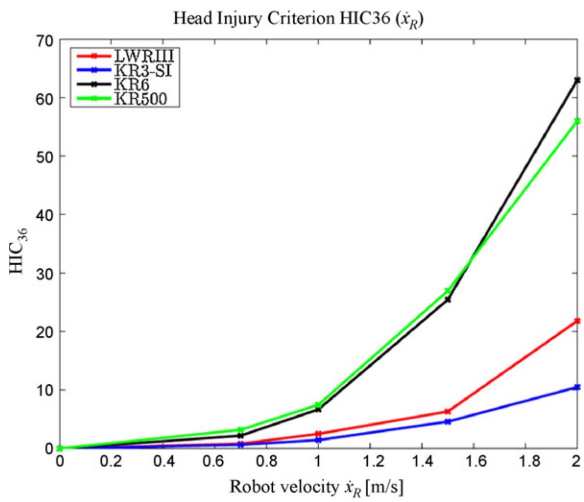

Fig. 26. Resulting HIC36 values at varying impact velocities for all robots, rated according to the EuroNCAP Assessment Protocol and Biomechanical Limits [54].

4. Component supply and logistics

4.1. The materials supply challenge

As shown in Section 3 the developments in robotic assist and handling technology as well as safety systems increase efficiency of cooperative and automated assembly. However the overall time and cost efficiency of assembly processes does not only depend on the optimal relation between human and automation system but also on the question, how assembly parts are fed to cooperative workplaces. As human–machine cooperation targets to higher flexibility and adaptability, the parts feeding process also needs to be highly flexible.

Several unpublished studies performed in Norwegian medium size manufacturing industries have revealed that much of the manual work effort in assembly is not in the primary assembly tasks. The task of fetching components from storage areas and bringing them to the workplace for assembly has in many cases been found to constitute 60–70% of the total work hours spent on assembly.

In automatic assembly solutions it has been found that more than 75% of the equipment cost is on feeders and transport systems that automates the logistics of assembly while the actual assembly operation equipment account for less than 20% of the total cost of a typical assembly line.

Nevertheless, much of the research in assembly automation has been focused on the primary assembly. The automation of logistics and feeding has not been studied to the same level. But this area needs much higher attention if the performance of automatic assembly shall be brought to the same high level as that found in parts manufacturing. Some interesting papers by Bley, Denkena, Jovane et al. has pointed out the challenges and opportunities for greater effectiveness and flexibility in automatic assembly [55–60].

The real challenge here is part feeding flexibility. Solutions to automation in feeding and logistics have existed for a long time, dating back to Henry Ford's assembly line for his model T automobile. But the majority of these solutions are rigid, mass production types. Where flexibility is called for, in particular where the need is flexibility for manufacture to order with lot sizes down to one unit, good solutions are missing.

4.2. Flexible gripping devices

The flexibility challenge starts already at the gripping stage. In a cooperative assembly between human and machine, the worker normally carries out complex handling operations, where the high senso-motoric abilities of the human hand are needed. Robots are inherently very flexible, but their performance is often limited by the ability to grip the object that shall be handled. Grippers that can handle the variety from hard to soft and limp materials are not commonly in use industrially, and the technology in this area is still developing.

In particular the problem of changing quickly between different gripping tasks is a challenge. This problem encompasses both the robot movement program and the gripper design. Much advanced work has been performed on universal multi-finger grippers, but these solutions have not seen any applications in ordinary industrial tasks. Furthermore there is a challenge in size variations, how to enable the same gripping device to switch between handling objects of millimeter size and meter size.

- Humanoid multi-finger grippers.
- Special purpose gripping systems.
- Gripping of limp, soft and "non-definite shape" objects.
- Large size range gripping.

4.3. Intelligent gripping

Fig. 27 shows the spectrum of today's gripping systems.

This figure is based on a classification of grippers with two criteria: flexibility and complexity of a gripper and costs of a gripper. This spectrum has two extreme positions: A two finger standard gripper is in the lower left corner of Fig. 27. On the one hand a two finger standard gripper has only a very low flexibility, but is on the other a very cost effective gripping system.

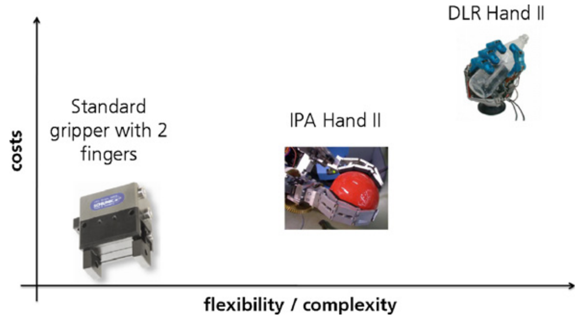

Fig. 27. Spectrum of today's gripping systems [61].

Fig. 28. Anthropomorph hand [62].

Complex hands like the DLR hand II or the Schunk SAH (Schunk Anthropomorphe Hand) (Fig. 28) are very complex gripping systems with several degrees of freedom. But the price of these systems can easily exceed the price of a robot system.

- Sensory systems for grippers.
- Picking unordered objects.
- Search mechanisms in gripping.

In order to fill the gap between these two extreme gripping systems Fraunhofer IPA developed the IPA hand I and the IPA hand II (Fig. 29) which is a good compromise between the flexibility and costs.

Both hands provide three possible gripping configurations (2 finger parallel, 3 fingers lateral and 3 fingers centric), which enable to grip a large number of different objects. Furthermore, both hands have a limited number of electric drives (the IPA hand I for example just needs 2 drives), and thus they provide a good cost effectiveness.

The IPA hand II is additionally equipped with a bio-inspired finger kinematics. This so-called Finray effect enables a self-adaptation of the fingers to the objects that have to be gripped [61].

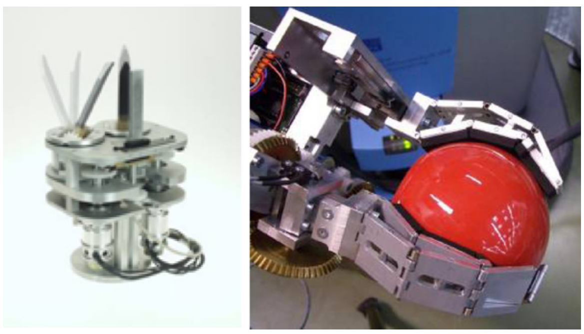

Fig. 29. IPA hands I and II [61].

4.4. General feeding subtasks

All automation solutions in manufacturing, whether it is in machining or cooperative assembly relies on some sort of automatic part feeding system to operate. Feeding parts into an operation is essential for all manufacturing operations; therefore automated as well as cooperative assembly requires automation of this process. Automatic feeding has however proved to be rather challenging because of the large diversity of parts. Even today there is no general theory or methodology that gives a straight road forward to an automation solution. There are on the other hand large libraries of solutions that can be applied to specific subclasses of the general class of automatic feeding.

To obtain an understanding of the feeding problem it is necessary to subdivide the general task into typical task classes that depend on component characteristics as well as process characteristics. Langmoen [63] and Rampersad [64] have proposed classification according to the following criteria:

- Production batch volume of a given unique component:
  - Large (mass production)
  - Medium
  - Small and single piece (produce to order)
- Component size:
  - Large (characteristic dimension >1 m)
  - Medium (characteristic size between 100 mm and 1 m)
  - Small (characteristic size between 1 mm and 100 mm)
  - Miniature (characteristic size < 1 mm)
- Component complexity
  - Simple shape, symmetric or semi symmetric
  - Unsymmetrical but simple shape
  - Complex shape
- Component stiffness:
  - Stiff, non-deformable objects
  - Semi stiff, deformable (like meat, rubber components, wires, etc.)
  - Limp objects (like textile, tissues, thin plastic sheets, etc.)
- Fragility:
  - Unbreakable by normal handling
  - Moderately fragile (requires some attention to handling forces)
  - Very fragile (must be handled very delicately).

This criteria list is not exhaustive, but it expresses the fact that very different considerations have to be taken into account when a cooperative or automated assembly system is considered. In the development of feeding systems such criteria can be used systematically to evaluate possible solutions and the likelihood of obtaining an efficient, workable automatic feeding solution.

4.5. Design for assembly applied to feeding problems

Formalized methods of analysis with respect to feeding systems exist. Boothroyd [65] developed an analysis method as early as 1979. This method focuses mainly on geometrical properties of the part and assumes high volume production. Later an alternative analysis method was proposed by Lien et al. [66]. In this analysis more parameters are used so that stiffness, fragility and size are brought into consideration. These two methods have both their shortcomings. This was realized by Rampersad [64] who has tried to combine the best elements from Boothroyd and Lien into the "House of Assembly" method. The house of assembly also introduces some QFD elements in the analysis. Furthermore there is a Japanese method for assembly automation analysis, the AREM [67]. This method relies on an expert evaluation of the automation solution. Common to all of these methods is the idea that the complexity of feeding and assembly can be characterized by some figure that expresses complexity of the feeding task. In the Boothroyd analysis method which has been trademarked DFMA there is in addition a calculation formula allowing the estimate of the cost of feeding and assembling a component [65]. This formula is limited to certain cases of automatic assembly in the large volume segment.

4.6. Sub-problems of the feeding task

The feeding task can be subdivided into four major steps; each of them requiring unique and very different techniques for automation. This subdivision assumes that the components initially are stored in large numbers in bulk, not oriented and fairly close, in the order of one meter or less, from the point of usage. Given this border condition, the feeding task comprises the following steps according to several authors [64–66,68,69]:

- *Separation*: One unique component is separated from the bulk volume.
- *Transfer*: The component is brought to a point very close to the point of pick up or treatment in the next stage of the manufacturing operation.
- *Orientation*: The component is brought from a general orientation into the specifically wanted orientation for the operation next in the process.
- *Positioning*: The component is positioned precisely within required tolerances for the next handling step in the process.

Some feeder techniques combine all these steps into one feeding device or system. Such systems are the most common ones in large volume manufacturing where small rigid parts are handled. For large parts, small volume, limp or fragile parts it is more common to see these steps of feeding separated.

4.7. Feeders for small parts in large volume production

Boothroyd [65] has described 17 basic feeder principles and mechanisms that are suitable for large volume manufacturing. It is characteristic that all of these combine mechanisms for the four subtasks of feeding into one device. It is common though that separation and transportation is related one part of the mechanism while orientation and positioning is relying on additional elements of the system. In addition, the orientation techniques are in some respects generic so that they may be applied in different feeding systems. Among the feeders described by Boothroyd only a few have been widely put to use. These are:

- vibratory bowl feeder,
- elevator feeder,
- belt feeder and
- drum feeder.

Some of these feeder techniques are very old as a basic principle. The vibratory bowl feeder is one of them. Still it has the reputation for being the most used feeder principle because of its simplicity and reliability. Over the last year some more flexible and sophisticated feeders have emerged.

The basic belt feeder as described by Pherson et al. [69] has been used as basis for several developments that increase its flexibility and reconfigurability. Pherson describes a system that uses simple photocell sensors to detect various part orientations. Active elements like pneumatically operated wiper blades are used to wipe away incorrectly oriented parts. The belt feeder is also the backbone of systems that use camera based active orientation.

The need for gentle feeding for particularly sensitive parts has led to the development of the vibratory brush feeder (Fig. 30). This feeder has the advantage of silent operation and small risk of surface damage of the part due to the part falling into a bulk storage area.

Moving step elevators represent another variation of recently developed feeders. This elevator is also more gentle in its handling as compared to ordinary elevator feeders. But it has not had great impact in the feeder market probably due to its somewhat complicated feeding mechanism.

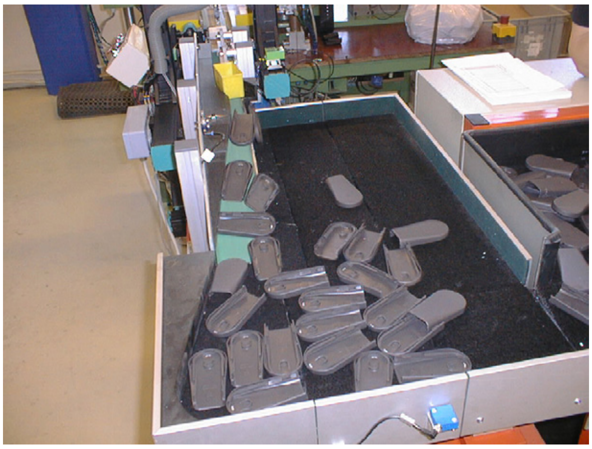

Fig. 30. Vibratory brush feeder for gentle feeding of fragile parts.

Fig. 31. Vibratory bowl feeder with active sensing reorientation. The vision system identifies the component for pick up. Unsuitably positioned components are returned to the bowl by a pneumatic pusher.

In spite of many options for feeding, the vibratory bowl feeder (Fig. 31) is the leading device by a solid margin. Its simplicity, versatility and reliability are the major reasons for its popularity. Despite this, it is one of the most typical "one part only feeders" which means that it can only be used efficiently for the specific part for which it is designed. This is mainly due to the fact that orientation devices are strongly integrated in the feeder design.

4.8. Large part feeding

The feeding of large parts seems to be a much more complex task than feeding of smaller parts. While small part feeders can accept parts in disordered bulk fashion large part feeding systems cannot operate the same way.

The borderline between small part and large part feeding is not very clear. But some indications about the borderline can be found in the rule of thumb saying that a vibratory bowl feeder should have a bowl diameter of approximately 10 times the largest dimension of the part to feed. For practical reasons bowl feeders are limited in size to around 1 m bowl diameter, setting the borderline between small and large parts to 100 mm.

In other studies [68] the borderline has been set to 150–200 mm. But there is no clear indication that this is a well defined borderline. It seems more to be a type of border set by the upper size limit for available feeders for bulk components.

Truly large parts can be seen as components having at least one dimension greater than 500 mm. For such parts no universal feeding principles seem to exist. There are however numerous special purpose feeding mechanisms, usually designed for a limited range of shapes and dimensions. Some examples of feeders in this category are:

- sheet metal feeders for stacked sheet metal,
- tube feeders and bar feeders for raw material to sawing and machining operations and
- de-stackers for cardboard in box raising equipment.

These feeders are only usable for materials with smooth surfaces like straight, un-machined bars and tubes, flat plate material and cardboard and other large component with clean simple shapes [70–72]. As soon as the part becomes formed into something "un-straight" none of these feeding principles are usable in their basic form. The feeding of more complex shapes thus has no general solutions available, nor does the literature give any indication of theoretical solutions for these large part feeding challenges.

4.9. Orientation mechanisms

Orientation of the component is an essential part of a feeder system. Bringing the part into its required orientation is a necessity for the next step in almost all manufacturing or assembly operations. Orientation devices are often seen as integrated parts of the feeder. But in almost all cases the orientation can be seen as a function independent from the separation and transportation part of feeding.

Basically there are two principles used for orientation [65]:

- Passive orientation which utilizes the potential and movement energy to create the necessary force to reorient or eject an incorrectly oriented part.
- Active orientation uses externally supplied energy to either reorient or eject incorrectly oriented parts.

In addition two different sensing methods are used to sense the part's orientation:

- Intrinsic sensing, that is utilization of geometrical features of the part to create the reorientation or sorting action. This is normally associated with passive orientation but can also to some extent be combined with active orientation. It is the only method available for sensing with passive orientation since it requires no external energy supply.
- External sensing utilizing some sort of sensing devices that can observe features that indicates the orientation of the part and can supply information from this observation to an active orientation device. Most active orientation devices rely on external sensing.

4.9.1. Passive orientation

Designing passive orientation relies to a large degree on the experience of the designer. But Boothroyd has presented a library of passive orientation elements [65]. The library is atomic in the way that each element shall have only one orientation effect (like reorientation around one axis). The wanted reorientation device for a specific part is then composed by selecting the orientation device elements that can give the wanted effect based on the available external geometrical features of the part. Edwardsen [73] has taken this as step further by investigating the properties of some reorientation devices and combining that with the movement pattern and energy available from a vibratory feeder to create a basis for precise prediction of the reorientation effect.

Nevertheless, all passive orientation methods are based on fixed geometrical elements that are not easily reconfigured. So even if reconfiguration is possible, the method usually requires manual effort with the associated time for reconfiguration. Therefore the passive orientation is still a method mainly suitable for mass production automation.

4.9.2. Active assisted gravity reorientation

In certain cases a hybrid solutions combining active and passive techniques are applied. The typical case is the use of gravity for reorientation, but some sort of active mechanism is applied to make gravity work in the way wanted. The simplest procedure is to push the part into a position where gravity will ensure proper orientation when the part tips over an edge [68]. Here the part must be fed in a well defined manner so that only the outcomes that give correct orientation after the act of gravity reorientation can occur.

Another more sophisticated method uses vision system in combination with a robot having only 4 DOF that can pick up randomly oriented parts on a table or conveyor. These parts should typically have a length/width ratio greater than one to make the action easier. The robot's two gripper fingers are equipped with small low-friction pivoting pads as grip area. When a part is lifted off its resting surface by a grip outside its center of gravity it will turn so that its center of gravity comes straight below the centerline between the gripping pads. A 90° reorientation around the *X* or *Y* axis is thus possible for a robot system with only rotation around the *z*-axis as a controlled orientation possibility.

These two examples show that hybrid reorientation systems that combine gravity with some sort of active repositioning can work efficiently in certain applications.

4.9.3. Active sensing for reorientation

- *Single point external sensing*: Point or single feature sensing, like micro-switches, photocells, inductive or fluidic sensors identify one single feature of the part. These devices are simple and reliable and can usually be applied to the actuation of one simple reorientation action. There are numerous examples of how these sensors are used to obtain a specific reorientation action. But the application of such sensing devices does seldom lead to greater flexibility of the feeder. So basically these sensors are applied in cases where intrinsic sensing is unreliable or cannot be applied.
- *Full feature sensing*: The full feature sensing relies on some kind of mapping of the complete external shape of the part. The most well known method in this area is the electronic camera which gives a two-dimensional image of the part, usually named vision systems. Pugh [74] described the basis of this method in 1983. Since then much of the development in the field has been concentrated on refinement of the methods and development of more cost effective solutions. The general strong reduction in cost for electronic devices has been a major driving force for the strong increase in vision system applications for part orientation.

Some of the solution described in the literature covers sorting out all unwanted orientations and returning them to a new feeding loop. This is a technique applied to vibratory bowl, vibrating brush and belt feeders [65]. A more efficient method is use the image information to realign the part when that is possible. This will in general give a substantial increase of the part feeding rate (Fig. 32).

Two-dimensional imaging has some shortcomings in identifying the orientation of complex three-dimensional shapes. Several methods have been investigated to overcome this.

- *Light section mapping*. In this method thin stripes of light are projected on the part at oblique angles. The light stripes form a pattern that are similar to the sections one would get by cutting the part along the plane of the light projection. Information about the angle of the light-plane combined with the position of points on the two-dimensional image of the light section enables a computation of the three-dimensional points on the parts surface that are seen in the light section. By interpolation between points on different light sections a complete the dimensional image of the part can be generated [74].
- *Multi camera three-dimensional vision*. This technique requires at least two cameras. By identification of the same point on the part's surface in two or more images with known position in space the points 3D coordinates relative to the cameras can be computed. The basic principle was described by Pugh [74]. Later there are numerous authors who have described refinements of this method [75]. Today the method works particularly well in cases where sharp corners and edges are visible so that edge detecting methods can be utilized to identify "same point" in two images.

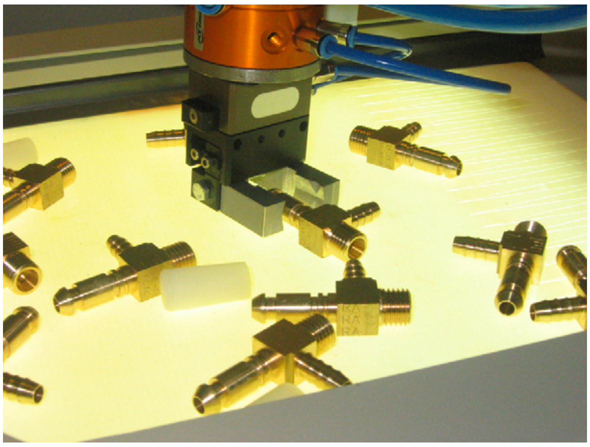

Fig. 32. Camera equipped belt feeder for feeding and picking arbitrarily oriented components.

The vision technology is slowly put to use in industry. Some interesting applications have been reported like sorting of castings in automotive part manufacturing [76,77] and robot based automation of flow assembly lines [78]. But these applications also reveal some practical challenges in keeping the camera systems operative in the sometimes rather harsh industrial environments.

4.10. Flexible component feeders

The state of the art in feeding is basically centered on the concept having a specialized feeder for each part. In recent research projects there has been a concentration on finding more flexible feeding principles that will handle variants of parts without mechanical rebuilding. In recent years such systems have appeared in industrial applications. These systems work well with certain applications [65,79,80].

The basic principle of multiple part feeding is to use the simple belt feeder introduced by Pherson [69] as a simple separator mechanism that presents the component on a surface where it can be easily detected. Then a suitable detection mechanism can be applied to identify individual parts and determine its location and orientation.

The grip action shown in Fig. 33 is a typical example of a gripping of one type of part among others.

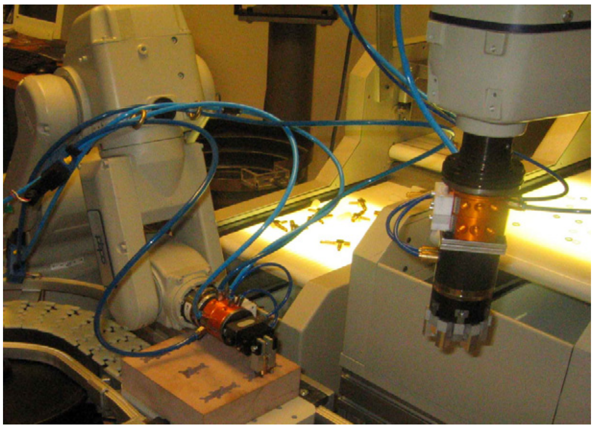

Fig. 33. Adept Flexfeeders for multi component feeding using electronic vision for component identification.

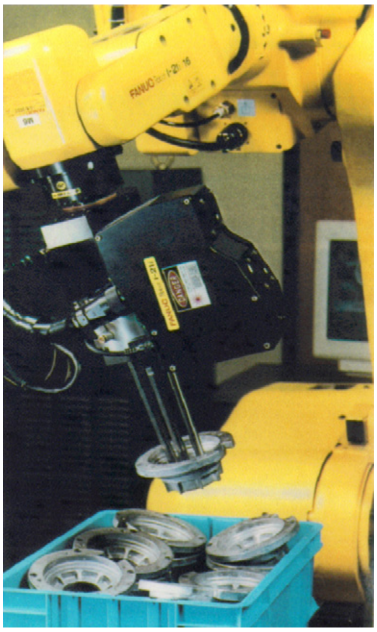

Fig. 34. Camera and force controlled gripper fingers used to pick up unordered castings [Fanuc].

Laboratory experiments in the NTNU assembly laboratory as shown in Fig. 34 have shown though that the time required to identify one single component among several different ones can take considerable time. The time for the automatic picking procedure will be longer than what can be obtained with dedicated feeder and orientation systems. But the advantage is that a changeover between parts can be performed very quickly, there is hardly any need for hardware changes. And for previously used components the software templates will be available and immediately applicable. The main challenge in flexible feeding seems to be the time required to empty a feeder of one type and replenish it with another type of component.

Another way of looking at flexible feeding is to eliminate the special feeding device altogether and rely on sensory system equipped robots for the heavy and monotonous task of picking components either from conveyors or out of storage bins. Here developments of bin picking systems show promises.

Fanuc has introduced a system that combines an arm mounted camera system with force sensors in the grippers that enables the robot to pick parts directly from a container or from a conveyor.

4.11. Flexible automated logistics

4.11.1. Advanced automated guided vehicle systems

The feeding of component feeders is another challenge. Automatic operation of assembly systems requires a steady flow of components from intermediate storage or part manufacture directly before assembly. Traditionally this section of the manufacturing system has been automated to a lesser degree since the frequency of operations is lower, and consequently the apparent economic justification is harder to reach.

But also in this area there are technical developments that points towards more flexible automatic transport solutions. Automated guided vehicle (AGV) technology has been used for many years, particularly in warehousing and large scale manufacturing [81–84]. This technology is now ready for a new step forward with the emergence of low cost advanced electronic systems and autonomous navigation systems that will make modern AGVs more cost effective and flexible, and thus also applicable to a much wider range of assembly systems [85–87].

In particular the emergence of trackless AGV systems bears promises of more efficient and flexible autonomous transport devices. In trackless solutions no fixed guide wires are needed. Instead of this the transport vehicle uses either onboard navigation systems that rely on observing fixed landmarks for navigation, or they use information transmitted from cameras in the area they move to get overall information about their position. These systems require much less of costly fixed guidance systems and are thus much easier to deploy and reconfigure.

4.11.2. Intelligent conveyor systems

Intelligent conveyor systems are other important new developments. Conveyors have gone from being simple belt systems with a constant conveying speed to becoming complex transportation systems that can route individual objects along paths that are tailored to the needs of a specific manufacturing process. The routes available will always be limited to those offered by the tracks laid down, but within these there are opportunities for much greater flexibility than in the old rigid one-way systems.

Systems frequently use some sort of identification system on transport bases (pallets) to determine the routing of each individual transport unit. It is thus possible to mix different products in different stages of the production process on one transport system. Each individual transport unit will be routed to its destination at each conveyor intersection according to the production process for this part as represented in the overall control system of the conveyor.

This type of transport enables the combination of manual and automatic stations along a core transport line. It also enables the combination of serial and parallel work stations in a process to obtain the most efficient utilization of the manual work force and the automatic machines in hybrid assembly lines as shown by Lien [4]. The use of manual workers for the complex finishing tasks on assembly lines give both greater capacity flexibility and higher overall productivity than fixed sequential assembly systems without the possibility for intelligent rerouting.

4.12. Intelligent warehousing

One challenge in assembly is to keep track of the amount in stock at all storage points in a system. This challenge becomes very large when the process is automated. Out of stock situations at any point lead to immediate stop of operations, and the need for manual intervention to replenish and restart.

Today we see very little of true automatic storekeeping applied to automated assembly systems. But the need is there. An assembly flow control system that keeps track of all the components in the system and orders replenishment to all storage points is needed for a system to operate truly automatic.

Today's ERP systems are well developed to handle the overall bookkeeping of the main storage areas in a company, i.e. raw materials, intermediate stock and finished goods. But the stock level of any of these storage areas is not updated in real time. For tight down to the minute follow up of production the ERP system is thus unable to provide exact information. In addition all the work in progress stock outside of the main storage areas is normally not kept track off. Thus there is a large "white spot" on the storage map in most factories. The problem of this "white spot" is overcome by most foremen and department managers through local notebook storekeeping to cover the needs of any department.

The developments in new sensor technology, in particular the development of RFID, offers great potentials for building solutions that have real time information about the status of all storage points [88–90]. These solutions should have accuracy of one unit which is necessary for reliable automatic operation. Such planning and monitoring systems are not yet available on the market. But the demand from industry for a tighter, real time control of all work in progress stock levels is increasing. At NTNU two ongoing research program address this task in an effort to develop next generation Manufacturing Execution Systems (MES) with real time stock control. The emergence of such systems will enable a more precise supply of components for assembly and minimize time loss due to out of stock situations.

Fig. 35. Cobotic system for feeding and positioning of large assembly parts.

4.13. Parts feeding with intelligent assist devices

An efficient cooperation of human and machine in assembly can often be realized in a way where the feeding of the assembly parts is executed by an automated handling system but the assembly process itself is carried out by the human worker. When a close interaction with contact of human and feeding system is possible with respect to safety requirements, the robotic feeding system may not only feed the assembly workpiece but also support the worker with positioning functionality.

Fig. 35 shows a cobotic rail crane system design from Fraunhofer IPK, which provides feeding of large assembly parts as well as support for positioning. For the safe and efficient interaction, the intelligent automation device also provides functionality for collision avoidance. Additionally, in order to give the worker free space for his work, the cobotic system after feeding returns to a defined position executing the so-called homing function.

5. Organizational and economic aspects

5.1. Requirements for flexible robot based automation

The ARFLEX project funded within the 6th Framework programme of the EU aims to enhance and extend the capabilities of a common industrial robot system. By means of advance control system and intelligent sensor devices ARFLEX displaces non-reconfigurable, proprietary and expensive automation technologies. Kus et al. analysed the requirements of small and medium enterprises (SME) [91]. The investigation was carried out among enterprises in Germany, Italy, Poland and Switzerland. The analysis contained questions related to the robotisation of the production line, the activities performed manually, automatically by the use of specialized machines, and by robots. Figs. 36–39 comprise essential results of the investigation, with respect to complexity of robotic systems, production batch sizes and changes in production lines of SME.

The goal of the enquiry concerned the identification of the limitations and imperfections of the robotic systems having the biggest influence on their deployment in the industrial applications.

In case of small enterprises the main hindrance is too small production batches. This result indicates that the market is still not served with solutions satisfying the requirements of the low-volume production system. In case of the medium-size enterprises, the deployment of the industrial robots is mainly limited by the high costs.

The most frequent batch changes can be observed in electronics and electrical equipment production. In this sector almost 60% of the batch changes consider the daily changes in the production. Also in other industrial sectors the daily changes in the production line are also prevailing and are more than 40%.

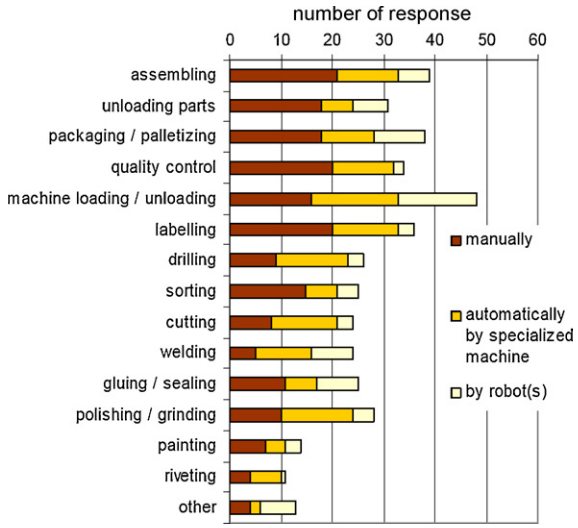

Fig. 36. Activities performed manually, automatically by specialized machines and by robots in the enterprises where robots are installed [91].

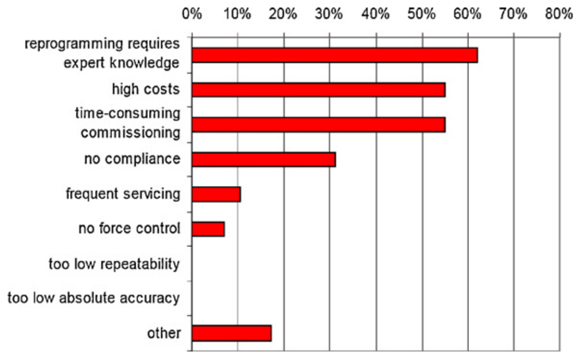

Fig. 37. Main disadvantages of using the robot in industrial applications [91].

5.2. Hybrid automation cost assessment

Fig. 40 shows the assumed cost potentials of hybrid automation compared with robotic workcells and automated transfer lines. According to this, hybrid automation has the biggest economic benefit in small and medium sized productions.

A more specific way to asses the costs of hybrid automation is the net present value (NPV), which is the sum of all cash inflow and outflow discounted back to its present value.

The following example shows how this method can be applied to assess the costs of hybrid automation. This example bases on the PowerMate example [10] shown in Section 2.3. Thus, the assembly consists of the following tasks:

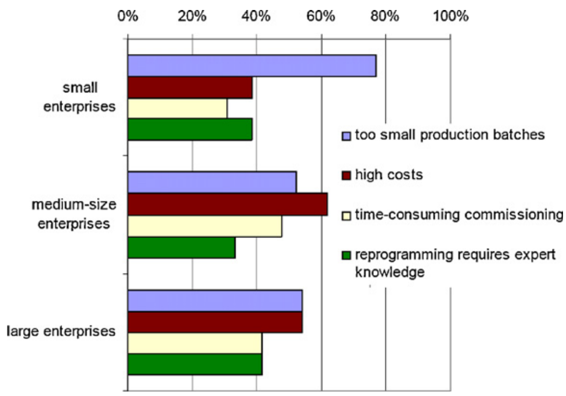

Fig. 38. The main obstacles for the dissemination of the robotic technology with respect to the size of the enterprise [91].

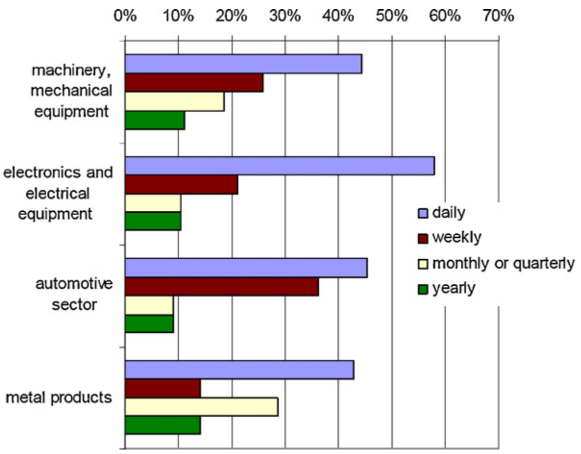

Fig. 39. The frequency of the changes in the production line (batch change) with respect to the industrial sector [91].

- *Task 1*: Prepare part A.
- *Task 2*: Grip part B out of bin.
- *Task 3*: Move B to A.
- *Task 4*: Precise positioning B.
- *Task 5*: Assembly A and B to AB.
- *Task 6*: Move part AB to part C.

As mentioned earlier tasks like handling of huge and heavy objects can be more efficient with robots while assembly tasks where high sensory skills are required can be more efficient with human beings. As consequence the tact times for a task differ if they are done by a robot, by a human being or in a hybrid automation scenario. Table 1 compares tact times of human and robot for the task sequence example.

Furthermore, in a hybrid automation scenario human worker and robot can work in parallel. In this scenario the task 1 can be done by the human worker while the robot performs tasks 2 and 3. As consequence the tact time of the hybrid system reduces to 100 s (instead of 140 s).

The tact time diagrams (Figs. 41–43) for these three alternatives look as follows.

Assuming that the needed output is 75,000 parts AB per year and that this company is producing in 2 shifts à 8 h at 200 days per year, the company will need either (Table 2):

- 10 (9.6) workers (human solution) or
- 3 (2.2) robot systems (automated solution) or
- 1 hybrid system with 3 human workers and 1 robot.

Furthermore we assume the following cash inflows and outflows for the investments.

According to these cash flows as the estimated numbers of human workers, workplaces and robot cells the three alternative solutions will reach the following net present values (Table 3):

- *manual solution*: 760,238.93 €
- *robotic solution*: 2,117,849.19 €
- *hybrid solution*: 2,754,257.19 €.

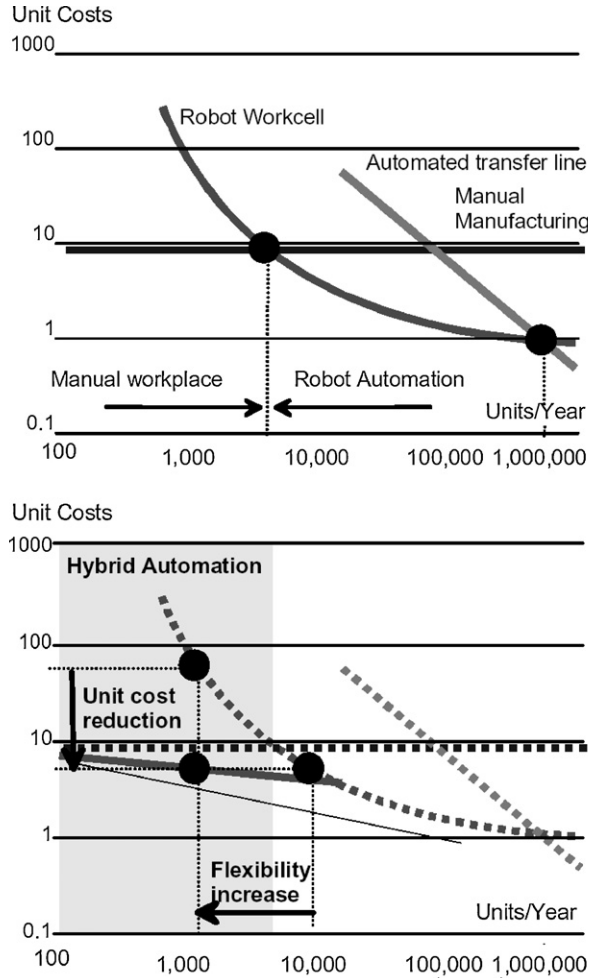

Fig. 40. Reduction of robot system costs compared to labour cost (above) and assumed cost potentials of future hybrid automation (below) [92].

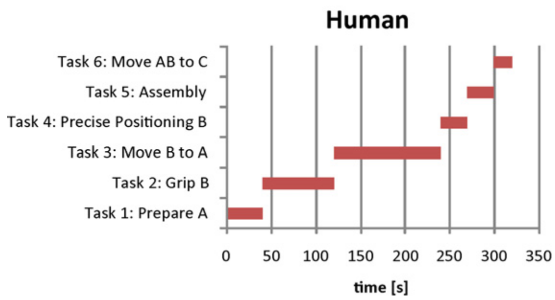

Fig. 41. Tact time diagram of human solution.

Table 4 shows as an example the calculation of the net present value (NPV) of the hybrid solution, which is according to the NPV method the best solution.

This calculation is based on several assumptions, e.g. that all alternatives produce the same quality and that all tasks can be

Table 1
Tact time comparison between human and robot.

Tact times in [s]	Robot: all tasks sequentially	Human: all tasks sequentially	1 and 2,3 parallel, rest sequentially	Best of
Task 1: Prepare A	40	40	40	40
Task 2: Grip B	20	80	20	20
Task 3: Move B to A	20	120	20	20
Task 4: Precise positioning B	60	30	20	30
Task 5: Assembly	60	30	20	30
Task 6: Move AB to C	20	20	20	20
Total tact time	220	320	100	160

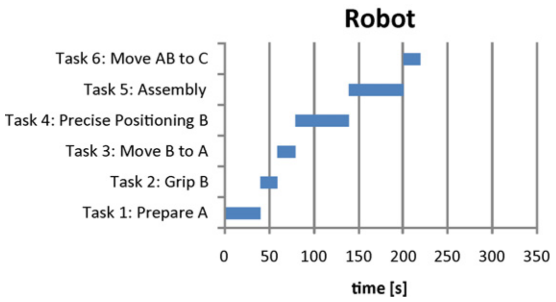

Fig. 42. Tact time diagram of robotic solution.

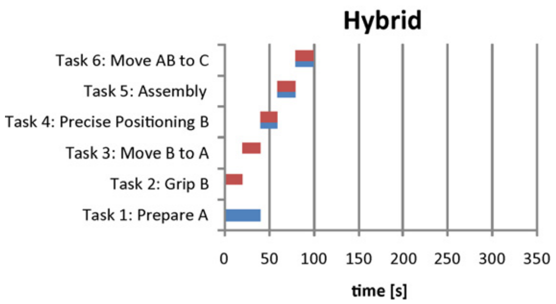

Fig. 43. Tact time diagram of hybrid solution.

Table 2
Output calculation for human, robot and hybrid system assembly.

	Robot	Human	Hybrid 1
Total tact time [s/pc]	220.0	320.0	100.0
Output per hour [pcs/h]	16.4	11.3	36.0
Hours per shift [h/shift]	8.0	8.0	8.0
Shifts per day [shifts/d]	3.0	3.0	3.0
Work days per year [d/a]	250.0	250.0	250.0
Total work time per year [h/a]	6,000.0	6,000.0	6,000.0
Output per year of 1 system [pcs/a]	98,181.8	67,500.0	216,000.0
Requested output per year [pcs/a]	215,000.0	215,000.0	215,000.0
Needed robots (integer)	3.0	0.0	1.0
Needed humans per shift	0.0	4.0	1.0
Needed humans total	0.0	12.0	3.0

Table 3
Cost comparison between human, robot and hybrid system assembly.

	Human	Robot	Hybrid
Invest per robot eel	0.00 €	−300,000.00 €	−325,000.00 €
Invest per workplace	−10,000.00 €	0.00 €	−15,000.00 €
Variable costs for robot cell p.a.	0.00 €	−5,000.00 €	−5,000.00 €
Variable costs for human worker p.a.	−50,000.00 €	0.00 €	−55,000.00 €
Revenues p.a.	750,000.00 €	750,000.00 €	750,000.00 €
Interest rate	10%	10%	10%

Table 4
NPV calculation for hybrid system assembly.

Hybrid	Outflow	Inflow	DCF
Year 0	−340,000.00 €	0.00 €	−340,000.00 €
Year 1	−170,000.00 €	750,000.00 €	527,272.73 €
Year 2	−170,000.00 €	750,000.00 €	479,338.84 €
Year 3	−170,000.00 €	750,000.00 €	435,762.58 €
Year 4	−170,000.00 €	750,000.00 €	396,147.80 €
Year 5	−170,000.00 €	750,000.00 €	360,134.37 €
Year 6	−170,000.00 €	750,000.00 €	327,394.88 €
Year 7	−170,000.00 €	750,000.00 €	297,631.71 €
Year 8	−170,000.00 €	750,000.00 €	270,574.28 €
NPV			2,754,257.19 €

done by a robot and by a human being. Furthermore aspects of illness of human workers and holiday regulations have not been taken into account. Nevertheless, this example shows that a high reduction of the tact time of a hybrid system compared to the manual solution and to the automated solution can be a good basis for economic advantages of hybrid solutions.

Lotter and Wiendahl [93] examined the performance of hybrid assembly systems, which include automated feeding and provisioning of parts. By this process time, which is not directly used for the assembly task can be reduced significantly and the overall efficiency of the production process is increased. This type of hybrid assembly was regarded in comparison with fully automated assembly for different products. In six of seven examined cases the costs per piece of a hybrid assembly were smaller than those of a fully automated assembly. The cost analysis given in [93] and [94] shows for the electric motors that the costs for a hybrid assembly cells needed for an output of 3000 pieces per day and also two cells needed for up to 6000 pieces per day are lower than those of a fully automated assembly system.

Beside other advantages of hybrid systems are:

- hybrid systems represent a form of rationalisation with an integration of human and by this giving positive impulses for occupation,
- assembly costs per piece for hybrid assembly are competitive for a wide range of lot sizes compared with fully automated systems,
- assembly costs per piece for hybrid assembly systems are economic even for relatively low lot sizes,
- the use of hybrid systems is characterized by relatively low investment, which helps to avoid false investments,
- the low degree of automation of hybrid systems increases their reuse value for a new product after finishing the production of an old one [93].

Further sources of economic advantages of hybrid solutions might be that a hybrid solution will produce a better quality or that some tasks in a given assembly scenario cannot or can only with high efforts be done with a manual solution or with an automated solution.

Based on experience achieved with intelligent automation devices (IADs) in assembly tasks, Stanley Automation estimates a reduction of injury costs, management costs and labour costs, which in total may reach an amount of 58% thus leading to a payback time of less than 1 month [95] (Fig. 44).

Fig. 45 shows an intelligent assist device which is used for handling of heavy loads. It is the first admittance display prototype in industry. Due to the admittance display structure of the control system the apparent inertia of the load can be reduced by a factor of 10 and more, so that the handling can be performed with low strain of the worker.

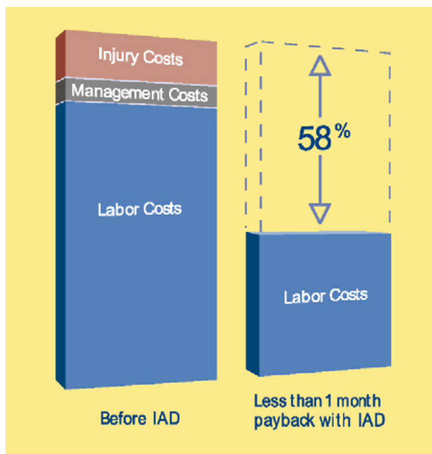

Fig. 44. Cost reduction by use of intelligent assist devices (IAD) [95].

Fig. 45. First admittance display prototype in industry [3].

5.3. Markets for hybrid assembly systems

In 2007 the worldwide stock of industrial robots reached the amount of about 1 million systems. The yearly supply climbed to about 60,000 industrial robots in Asia/Australia, 30,000 in Europe and about 20,000 systems in the Americas. While handling operations still is the main field of application, other fields differ in these regions. Although automotive industry is still the main customer for industrial robots, a significant growth can be observed in non-automotive sectors such as glass or food industry. Beside others improvements in force sensing, environment recognition, human–machine-interfaces and safety system technology are forecasted to be future technical trends [96]. These trends are significant enablers for hybrid human–robot operation.

An exemplary look to Europe shows the major market conditions for hybrid assembly. For these systems the target industries (automotive, household appliances and aircraft) face strong global competition and represent a major part of the European manufacturing industry. Any effort to improve the competitiveness, productivity and market responsiveness of these industries would be extremely important for Europe. The automotive industry employs 2.2 million people in production in nearly all member states of the EU. There are 380,000 SME's in the supply chain for the automotive industry in Europe. In 2002 global production of passenger cars and light and heavy trucks was just over 59 million units. The main vehicle-producing areas are the Asia-Pacific (19.3 million), western Europe (17.4 million) and North America (16.8 million). The turnover of European carmakers over the last few years has been on average 340 billion Euros per year. The European industry of household appliances employs 200,000 people directly and represents a yearly turnover of about 35 billion Euros. 40,000 SME's are suppliers for that industry. Approximately 50 million large appliances (washing machines, refrigerators, etc.) and 200 million small ones are produced in Europe per year. The aerospace manufacturing industry had in Europe a turnover of 81 billion Euros in 2003. Over 435,000 people are directly employed in high-quality jobs. Its business has a pervasive influence up and down the supply chain, beyond the sector to some 80,000 SME's within the European Union.

5.4. Hybrid assembly in automotive industry

In automotive industry the degree of automation in assembly mainly depends on two aspects: costs and complexity.

Power train assembly in western European countries is fully automated. Manual operation is typical for assembly of flexible interior parts of the car. In this area, automated handling with a robot is difficult due a lack of automated gripping flexibility and sensitivity and also because of danger of surface damages of the component. Manual or hybrid assembly tasks in automotive production are normally handled within 20–30 assembly stations. According to an unpublished internal analysis of assembly tasks of a major German automotive company, serious savings can be made by use of semi-automated flexible robotic systems for faster feeding of workpieces to the worker. By this, manual work load could be reduced by about 30 min per car.

This can be achieved by a hybrid assembly structure where handling for the final assembly step is fulfilled by use of the outstanding senso-motoric ability of the worker in combination by efficient support by intelligent assist systems (IAS) [96,11]. An important advantage of IAS is the abdication of safety equipment, which normally is needed, when feeding and handling of workpieces is done by robots close to the worker.

In Europe robot based handling and assembly operations determine more than 65% of the robotic market. These are application fields, where higher flexibility of hybrid systems can essentially improve the production process. In Asia and the Americas, cleanroom applications for robotics were increasing whereas assembly was decreasing in 2007 [96]. These facts may be regarded as indicators for a future stronger diffusion of hybrid robot based assembly in Europe compared to Asia and the Americas. The ongoing rapid changes in global markets especially in the automotive sector will have a significant influence to the robot market in the future. The relation between fixed and variable production costs which essentially determines the use of purely automated or hybrid assembly systems will certainly be affected by these dynamic changes.

6. Conclusion and outlook

The close cooperation of human and machine in hybrid assembly is motivated by the increased need for flexibility, adaptability and reusability of assembly systems. Hybrid assembly systems can essentially reduce the amount of fixed production costs in relation to variable costs. The effectiveness of these systems depends on the lot size, but also on the design of the cooperative workplace and its automated systems. The overall effectiveness of hybrid assembly also depends on the intelligent feeding of workpieces to the cooperative workplace.

An essential precondition for the time efficient close cooperation between human and machine is the safety of the worker. A lot of research has been carried out in this field in recent years and first sensor systems for the surveillance of the interaction between human and robots are available on the market.

The research in the field of intelligent assist devices (IAD) that efficiently support the worker is the basis to keep the worker in the loop in order to utilize his cognitive and senso-motoric advantages for highly flexible assembly. The support functions of IADs comprise safety as well as reduction of physical strain and efficient synchronisation between worker and automated systems.

Future research will have to focus on different aspects for highly cooperative hybrid assembly. The robustness of the system parts for safety, load reduction and others will have to be increased in order to extend the field of applications. A new challenge will be to improve the cooperation of human and machine not only for a single human but also for a group of workers that have to fulfil a common task supported by one or more machines at the same time (Fig. 46).

The close cooperation between human and machine may in the future also change the way that automated systems will be programmed. It can be foreseen, that a wide range of automated cinematic systems such as robots will in the future include interfaces for efficient teach modes based on the direct force coupled interaction between human and robot.

The human oriented automation approach may generally lead to a change in the design principles for robots. Today design of industrial robots is focused for accuracy. Control with application of external sensors is needed for stable and safe interaction. In long term solutions the design of intrinsically safe robots will focus on safety and sophisticated control will provide accuracy.

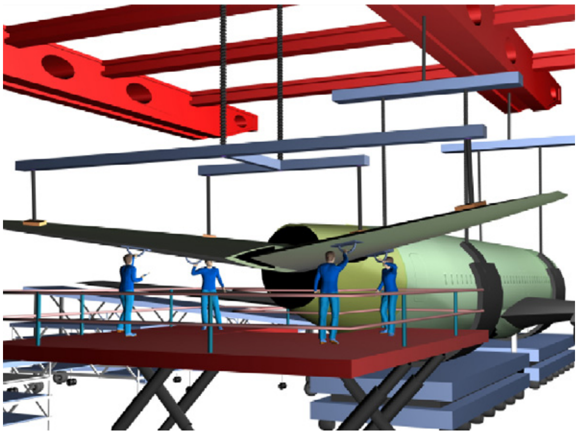

Fig. 46. Application of cobotic devices in future human–robot–human interaction for airplane assembly [97].

By this, the next generation of robots will interact with human directly for cooperative manipulation, where the robot is responsible for load-bearing and precision whereas the human can contribute with sensing, intelligence and skills.

Generally the advantages of a close cooperation between human and intelligent assist systems in assembly lines build a basis for a more flexible and also more sustainable way of assembly and disassembly in the future.

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